# NASA RESEARCH ANNOUNCEMENT

# PROPOSAL INFORMATION PACKAGE

## Next Generation Ion Engine Technology

This Proposal Information Package describes the technical objectives and other information required in support of the NASA Research Announcement for the Next Generation Ion Engine Technology (NRA-01-OSS-01, section A.9.2). Section 1.0 provides detailed descriptions of the objectives for each technology area. Section 2.0 describes the Design Reference Mission. Section 3.0 defines the state-of-the-art in ion engine performance.

## SECTION 1.0
## Next Generation Ion Engine Technology

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Section 1.0

The ISP Program supports the development of advanced propulsion technologies that reduce cost, mass, and/or trip times associated with NASA's science missions, especially to deep space, that are approved as part of the program of NASA's Space Science Enterprise. Background information about the Office Of Space Science (OSS) ESS science theme is available on the World Wide Web site at: http://spacescience.nasa.gov. Derivation of proposed ion engine system technology options and architectures should be guided by the mission envelope given by the Deep Space Design Reference Mission (DSDSDRM) presented in Section 2.0 of this NRA and the knowledge of potential future target destinations for the Outer Planets Program (as reflected in the referenced web site). In addition to these sources, the proposer should keep in mind the issues of reliability, redundancy, and de-rating when developing system architecture. This NRA emphasizes the following high-priority technologies (of approximately equal priority):

- Electric propulsion thrusters (EPT's)
- Power Processing Units (PPU's) to convert solar array power to forms useful for the EPT's
- Propellant Management
- New technology integrations (including the EPT's, PPU's, and propellant management concepts)

Researchers considering research and development of next generation ion engine technologies should also be cognizant of the state-of-art as represented by the ion propulsion system for the Deep Space-1 (DS-1) MISSION (SEE section 3.0 for a summary of the DS-1 characteristics and http://nmptechvalreports.jpl.nasa.gov/DS1/IPS Integrated Report.pdf for greater detail) and the specialized facility and ground support equipment (GSE) necessary to assure high fidelity testing of the performance, lifetime, and unique interfaces of ion propulsion systems. Proposers should note that the thermal environment established by the DSDRM, described in Section 2.0, differs greatly from that which drove thermal requirements of the SOA DS-1.

Under this NRA, ion engine propulsion technologies at the component and system level are expected to reach a Technology Readiness Level (TRL) of 5, with significant progress made toward a TRL of 6 three years after award of a Phase 1 contract (See Table 1 for TRL definition).

| | | | |
|---|---|---|---|
| | Syste m Test, | | Actual system "flight proven" through successful mission operations |

| | | | |
|---|---|---|---|
| System / Subsystem Development (6-8) | | TRL 8 | Actual system completed and “flight qualified” through test and demonstration (Ground or Flight) |
| | | TRL 7 | System prototype demonstration in a space environment |
| | Technology Demonstration (5-6) | TRL 6 | System / subsystem model or prototype demonstration in a relevant environment (Ground or Space) |
| Technology Development (3-5) | | TRL 5 | Component and / or breadboard validation in relevant environment |
| | | TRL 4 | Component and / or breadboard validation in laboratory environment |
| | Research to Prove Feasibility (2-3) | TRL 3 | Analytical and experimental critical function and / or characteristic proof-of-concept |
| Basic Tech. Research (1-2) | | TRL 2 | Technology concept and / or application formulated |
| | | TRL 1 | Basic principles observed and reported |

Table 1. Technology Readiness Level (TRL) Definition

For further clarification and for this NRA only, a TRL of 5 implies that new technology components have been developed to an engineering model level and have met the appropriate environmental acceptance levels represented by the DSDRM, described in section 2.0, as well as demonstrated a significant level of component life.

- The system components, the EPT, PPU and Propellant Management System must have passed performance acceptance and the relevant environmental tests at the Engineering Model (Brassboard) level with flight representative packages.
- Integrated system acceptance tests that assure high confidence in the ability of individual components to perform as an integrated propulsion system must also be completed.

A TRL of 6 implies a full life test of the propulsion system in a relevant environment (single string). Life testing is desired of integrated new technologies developed under this NRA. However, due to the limited performance period of this NRA, it is realized that full qualification levels may not be achieved.

Nevertheless, this research announcement is for research and development efforts that are commensurate with the TRL goals stated above in order that such systems would be available for consideration by proposers of flight missions by 2005. During research and development of these technologies, proposers should keep as a metric, the future cost associated with implementation of the technology. Proposals should include all assumptions (including environments derived from the DSDRM) when describing proposed research and development of technologies, architectures, system capabilities, and performance metrics for the purpose of evaluation.

## 1.1 Electric Propulsion Thrusters (EPT's)

Requirements for advanced EPT's are directly traceable to the DSDRM contained in Section 2.0 and other potential ESS missions referenced at the OSS ESS World Wide Web site. It is anticipated that the optimum specific impulse will vary with specific mission. Therefore, a thruster concept that provides flexibility in ISP is desirable. For reference, the overall spacecraft power for the DSDRM and other ESS missions relevant to this NRA typically are between 20 and 30 kW at Beginning of Life (BOL) at one Astronomical Unit (AU) from the Sun. Significant advances over the state of the art technology that are desirable to demonstrate include:

- Capability to achieve propellant throughput at levels based on the DSDRM and required margins for qualification for flight use
- Operation at maximum and throttled power levels
- Increases in maximum specific impulse of at least 30 percent over that of the SOA EPT as identified in Section 3.0
- EPT specific mass comparable to or less than the SOA EPT
- EPT efficiencies that exceed the SOA EPT efficiencies (across all power levels)

Proposals solicited by this NRA should address both phases as described below.

A. Phase I

The overall objective of Phase 1 is to provide sufficient theoretical and experimental knowledge to enable prudent selection of an EPT concept for subsequent research and development in support of requirements represented by the DSDRM. Specific Phase I objectives include:

- EPT requirements definition. EPT requirements must take into account the lessons learned from the DS-1 program and models that predict performance, life and unique interfaces of EPT's.
- Demonstration and evaluation of laboratory class, or more mature, EPT's over the required range of power and specific impulse, as well as demonstration of a concept that meets, as a minimum, the above stated increases over SOA.
- EPT lifetime prediction. This prediction should be supported by a combination of one or more of the following; component traceability and analyses, accelerated life test or development testing for sufficient time to validate the key assumptions in the analyses (used to predict propellant throughput and operating life), and identification of lifetime limiting phenomena of the selected concept.

Phase I Activities for EPT's are limited to a one-year duration.

B. Phase 2

The overall objective of Phase 2 is to develop an EPT to a TRL level of 5 with significant progress toward a TRL of 6. The effort should include sufficient performance, lifetime, and interface evaluations to reduce risk for subsequent developments for future ESS missions. Specific Phase 2 objectives include:

- Demonstration of the EPT's capability to be integrated into a practical ion engine system, which includes provisions for mechanical, thermal, other environments (such as radiation) and spacecraft integration considerations.
- Analytical and experimental evaluations to assess the EPT's capability to meet the selected throughput/lifetime, performance, and environmental requirements/interfaces required by the DSDRM.
- Performance of at least one single long-term test in vacuum of the final EPT configuration. This shall demonstrate a throughput capability of a significant fraction of that represented by the DSDRM.
- Evaluation of critical and unique interfaces to assure compatibility with the spacecraft and operations of future ESS missions. This should include evaluation of particle plume characteristics and impacts, conducted and radiated Electromagnetic Interference (EMI), electrical power, thermal, and thrust vector stability.

Phase 2 activities are limited to duration of two and one half years.

1.2 Power Processor Units (PPU)

PPU's are required to convert the spacecraft power into forms useful for the EPT. It is desired that proposals include innovative PPU concepts. Basic NRA objectives for the PPU include:

- An increase in the PPU power level and increase in specific power (kW/kg) over SOA
- An increase PPU efficiency over that of the SOA PPU
- Ability to operate under the environmental conditions required by the DSDRM

A major objective is to meet the challenges stated above as well as those presented by the DSDRM provided in Section 2.0 while providing compatibility with the EPT. Proposals solicited by this NRA should address both phases as described below.

A. Phase 1

It is an objective of Phase 1 to have a breadboard version PPU that meets spacecraft and EPT functional requirements. It is also an objective to identify long-lead parts for mature PPU concepts and any parts that require additional development to satisfy the PPU requirements. Major activities to achieve these objectives include:

- Design of a PPU that satisfies the requirements of a selected EPT concept and establish the interface requirements represented by the DSDRM. The requirements, design and supporting analysis, and documentation should be at maturity sufficient to enable a subsequent fast-paced and efficient development.
- Demonstration of pathfinder circuit concepts (final circuit concepts required for the Phase 2 advanced technology PPU) for critical PPU circuits including those associated with ion acceleration, ion production, and PPU interfaces with spacecraft power and command/control subsystems.

Phase 1 activity for PPU's are limited to one-year duration.

B. Phase 2

The overall objective of Phase 2 is to provide a PPU with a TRL level of 5, with significant progress toward a TRL of 6 that is fully compatible with the EPT, proposed system architecture, power levels, and environments. The proposal should outline a well-structured program that identifies and resolves component and circuit design issues. Issues including long-term, reliable thermal-vacuum operation in a packaged configuration, single event upset tolerance, radiation environments and thermal control should be addressed as well as mechanical and electrical compatibility with EPT (to include ability to assure operation in all mission phases including startup, full throttling range steady state operation and fault recovery), and spacecraft subsystems and functions. Phase 2 activities are limited to two and one half year duration.

1.3 Propellant Management (PM)

The propellant management subsystem accepts propellant from the storage unit and distributes and controls the flows to the individual EPT's as required. The SOA PM concept on the DS-1 mission was one of the heaviest single elements (12.5 kg) of the DS-1 propulsion system. With the possibility of utilizing multiple EPT's to meet the requirements represented by the DSDRM (where heavy PM masses would deeply impact payload capabilities), the objectives for activities under this area are as follows:

- Demonstration of a PM system with significant mass and volume reductions over the SOA
- Evaluation (by analysis and test) of a PM system that maintains or exceeds the lifetime and power of efficiency of the DS-1 PM concept
- Capability of a PM system to assure the proper propellant purity levels of propellants supplied to the EPT's to insure system lifetime.

Proposals solicited by this NRA should address both phases of this task as described below.

A. Phase 1

The objective of this task is to demonstrate the feasibility and practicality of PM concepts with potential to meet the PM flow and life requirements represented by the DSDRM. The ability of concepts and components to meet life requirements are to be determined by both analysis and supporting test. The components should be capable of meeting life requirements for qualification (factor of 1.5) of hardware for a mission represented by the DSDRM.

The concepts should also significantly reduce the mass of the PM from that of SOA. Of particular interest are:

- Demonstrations of PM component concepts that regulate and control flows over the range of input and output conditions anticipated in flight
- Demonstrations of components under relevant environmental conditions, such as temperature and ground exposures
- Sufficient component life testing to provide high confidence for subsequent development of higher-maturity PM systems
- Analysis of proposed concepts to ensure propellant purity essential for EPT life

Phase 1 activities are limited to a one-year duration.

B. Phase 2

The overall task objective is to provide a PM concept with a TRL level of 5 with significant progress toward TRL of 6. Potential activities and demonstrations to achieve this objective may include:

- Validation of the PM components/system with typical propellant conditions such as temperatures, pressures and contamination levels
- Demonstration of the basic PM components to operate reliably under environmental conditions presented by the DSDRM contained in Section 2.0
- Simultaneous operation of multiple EPT’s with the advanced PM concept including throttling
- Maximum amount of life testing achievable when integrated into the Ion engine system

The command and control interfaces for the Propellant management system are to be proposed. Interactions of the PM with the PPU and an executive (spacecraft) controller are required for system level testing and may be performed by use of a simulator. Phase 2 activities are limited to duration of two and one half years.

1.4. New Technology Integration

Future ESS missions may require new EPT, PPU, and PM technologies and the simultaneous and extended operations of multiple thrusters. It is an overall objective of this NRA to solicit proposals to integrate and demonstrate the functionality, reliability, and lifetime capability of both a single string and a system level configuration (which may utilize multiple thrusters) and to evaluate the critical internal and external interfaces within the period of performance covered by this NRA. Activities under this section of the NRA should allow for the:

- System integration and demonstration of the EPT, PPU, and PM technologies
- Characterization of the new EPT, PPU, and PM technologies at the system level
- Quantification of performance and verification of analysis
- Mitigation of risk to mission planners that may consider implementation of EPT, PPU) and PM technologies in future missions

Technology Integration activities will also be conducted under two Phases with the majority of effort focused on Phase 2. Proposals solicited by this NRA should address both phases of proposed activities.

A. Phase 1

The objective of Phase 1 is to perform any necessary preliminary designs of Ground Support Equipment (GSE) items or possible required facility modifications (all of which should be identified in the solicited proposals) to a fidelity that will allow the completion of these items and to identify long lead items to support Phase 2 activities. Included in this may be the selection of gimbals (if required for future integrated testing). It is not the intention of this NRA to develop an advanced gimbals system at TRL > 5. For the Phase 2 testing, state of the art gimbals may be used or the proposer may choose to do low level technology advancement in this area. Preliminary analysis of the integrated testing may also be performed. In support of possible phase 2 funding, a test program should be defined.

B. Phase 2

The objectives associated with Phase 2 activities in this area involve the integration system level demonstration and evaluation of the components developed under Sections 2.1 through 2.3 of this NRA. Specific objectives include:

- Demonstrations of the compatibility of single string combinations of advanced EPT's, PPU's, and PM systems of increasing levels of maturity (Note: these initial activities may occur in Phase 1 if hardware and funding are adequate)

- System level integrated testing (with the intended number of operating thrusters) to evaluate ion propulsion system interfaces and assures overall compatibility and lifetime in the intended operational configurations. Issues to be addressed include as a minimum potential interactions between EPT plumes; lifetime impacts as a function of number, operating condition, and spatial configuration of the EPT's; gimbal angle effects on other EPT operations and lifetimes; compatibility of selected PM concepts with multiple/throttled EPT operations; the degree of linearity of radiated EMI with number and location of thrusters; thermal interactions; etc. The proposer should address any other significant issues not addressed above.

The hardware and test durations selected for these demonstrations and evaluations should be with elements of the minimum maturity and test times essential to achieve the overall objective. A special concern is the facility and ground support requirements necessary to assure high-fidelity information on the performance, interfaces, and lifetime of the multiple thruster systems. Proposers should be cognizant of prior efforts directed at that issue and provide justifications (see Section 3 below) for the selected facilities and key GSE approaches. Phase 2 activities are limited to a duration of two and one half hears for all activities including fabrication and installation of all GSE and facility modifications.

## 1.4 Special Technical Considerations

Ion propulsion systems have very specialized and nonstandard testing, facility, and ground support requirements that are not typically available in the aerospace community. High-fidelity information, particularly with high-power EPT's, demands appropriate experimental approaches. Facility issues and considerations should be addressed for each element of the next generation ion propulsion system. Facility operating costs are also a substantial issue for ion engine research. It is not the intent of this NRA to fund large amounts of facility development. Therefore, it is desired to identify cost-effective experimental approaches sufficient to accomplish the objectives of the proposed efforts.

# Section 2.0
## DESIGN REFERENCE MISSION

The Design Reference Mission (DSDRM) contained in this section provides an envelope of anticipated requirements based on preliminary studies of technologies and possible Outer Planets destinations. The DSDRM does not provide a destination or a total mission trajectory, but provides the necessary information (along with Section 1.0) to develop requirements during the period of expected operation of the solar electric propulsion system. The requirements listed below provide enough information that the proposer should not find it necessary to perform a detailed trajectory analysis.

**DSDRM Ion Propulsion In-Flight Operations Scenario**

Electrical Power Source

The power source is a lightweight triple-band-gap solar array with nominal 28% cell efficiency at 1 AU. The design operating voltage may be selected for optimization of the propulsion system between 28 VDC and 100 VDC. The actual operating voltage may vary with distance from the Sun from about 80% of the design voltage, at minimum solar distance and maximum power, to about 150% of the design voltage at 3 AU and minimum power. For purposes of this DSDRM, the proposer can assume a solar array that provides at a minimum 150 W/kg.

The electric propulsion system power processors must isolate the solar array from thruster arc faults or other malfunctions, which could drive the array output to zero volts and shut down the spacecraft. Alternatively, spacecraft power may be derived from separate solar cell strings on the arrays so that voltage fluctuations on the propulsion power source do not affect the spacecraft. *[The offeror should recommend which alternative is preferred.]*

The nominal system design provides a spare power processor and thruster. Should a failure occur such that less thrust is available, the trajectory is at that time redesigned to provide the best mission profile available with reduced power.

Payload Mass

The final payload mass that the proposed ion engine system (science payload, spacecraft bus and associated systems, and any propulsion required at the destination) must be capable of delivering will change based upon destination as well as specific mission requirements (fly by vs. orbiter, etc.) To this end, the DSDRM will establish the following guidelines for purposes of this NRA only:

- Payload mass to destinations as far as Saturn may be as great as 1,400 kg.
- Payloads intended for destinations beyond Saturn are not expected to have a mass greater than 850 kg.

The total launch payload mass will have to accommodate the final destination payload mass as well as the propulsion system and must meet the capabilities of the class of launch vehicle chosen for this DSDRM. Given the above payloads, the proposer should be aware that a reduction in Mission trip time is considered desirable.

Launch

The vehicle is launched from KSC on an ELV not to exceed the cost and capabilities (payload mass, volume constraints, etc.) of a Delta 4 Medium class (not to exceed a Delta 4 Medium 4,2 or 5,2) of launch vehicles. The proposer should be aware that it is desirable to minimize launch vehicle requirements.

Startup

After upper stage separation, the vehicle establishes attitude control and deploys the (nominal 30 kWe array, positioned to provide 25kWe at 1AU) solar array. Checkout tests are completed, and array power is then available to start the electric propulsion system. The propulsion system is started and powered flight begins.

Operation

The early part of the mission starts at 1 AU and will eventually increase in solar distance to about 2.5 AU. Accordingly, the power available drops from the 25 kWe to approximately 4.8 kWe, and array optimum voltage increases.

An unpowered coast is inserted into the initial trajectory profile, to provide for trajectory management, which is assumed to be about 10% of the nominal powered trajectory time. Powered flight is then resumed.

The powered trajectory loops around the Sun and reaches a minimum solar distance of about 0.7 AU where the maximum power available is maintained by solar array manipulation to be approximately 25 kW. This trajectory allows for a possible Venus Gravity Assist (VGA). This DSDRM utilizes a VGA instead of an Earth Gravity Assist to avoid some of the environmental and safety concerns associated with the trajectory if an RTG is flown. The trajectory then initiates the final destination transfer, going to a maximum powered flight distance from the Sun of about 3 AU where power available is about 3.3 kWe. This value may vary based on efficiencies but for the purpose of the DSDRM the inverse square rule was utilized and a simple reduction by $r^2$ is assumed. At approximately this distance, when the trajectory reaches an insertion point where unpowered flight attains the desired destination encounter, the electric propulsion system is shut down and jettisoned from the vehicle. The final Delta V requirements for the DSDRM will have a range from 10 – 13 km/second. At anytime during operation, the systems should be able to withstand events associated with operation over the described trajectory, such as solar flares.

Note that the electric propulsion system must deal with more than a 10:1 variation in available power and about a 2:1 variation in power source voltage. At high power availability the electric propulsion system must limit power to the thrusters to their maximum capability. At low power availability the thrusters must be operated in a throttled (reduced current) condition while delivering required Isp at or near design efficiency. A choice may be made between shutting down some thrusters versus operating a greater number (or all) at further reduced current. If the system design uses thruster gimbaling for center of gravity tracking and roll control, it is necessary to operate at least two thrusters to maintain roll control.

# Section 3.0
## SUMMARY OF DS-1 CHARACTERISTICS
State-of-the-Art Capabilities of Ion Propulsion

1. Ion Thruster

1.1 Performance

| Input power to EPT, kW | Specific impulse, s | Thrust, mN | Thruster efficiency |
|---|---|---|---|
| | | | |
| 2.3 | 3120 | 92.4 | 0.62 |
| 2.13 | 3170 | 78.2 | 0.63 |
| 1.59 | 3110 | 57.8 | 0.61 |
| 1.07 | 2930 | 37.2 | 0.55 |
| 0.53 | 1970 | 20.6 | 0.42 |

1.2 Specific mass at maximum thruster power = 3.6 kg/kW
1.3 Demonstrated xenon throughput at least 140 kg

2. Power Processing Unit (PPU)

2.1 Performance

| Line voltage, V | Input power to PPU, kW | PPU efficiency |
|---|---|---|
| | | |
| 100 | 2.47 | 0.914 |
| 100 | 1.51 | 0.931 |
| 100 | 0.51 | 0.917 |

2.2 Specific mass at maximum input power = 6.0 kg/kW
2.3 Maximum power density = 0.18 $W/cm^3$
2.4 Safe operating bus voltage envelope at 55 $^oC$ baseplate: bus voltage from 80 V to 120 V
2.5 Demonstrated operational life at least 12,000 hours.

3. Propellant Management System (PMS)

3.1 Mass

| | | |
|---|---|---|
| Storage tank for 81.5 kg of xenon | 7.94 kg | |
| Plenum tanks (2) | 3.07 kg | |
| Xenon flow control | 7.78 kg | |
| Tubing, fittings, wiring, connectors | 1.42 kg | |
| Total mass | | 20.21 kg |

3.2 Largest component volumes for PMS are 2 plenums at 3.7 liters each.
3.3 Demonstrated operational life at least 12,000 hours.

Note: Information was obtained, in part, from:

Bond, T. A. and Christensen, J. A., “NSTAR Ion Thruster and Power Processors,” NASA CR 1999-209162, November 1999.

Ganapathi, G. B. and Engelbrecht, C. S., “Performance of the Xenon Feed System on Deep Space One,” *Journal of Propulsion and Power*, Vol. 37, No. 3, May-June 2000, pp. 392-398.